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The Bone Mineral Density in Childhood Study: Bone Mineral Content and Density According to Age, Sex, and Race

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Context: Low bone mass may increase risk of fracture. Several chronic medical conditions, medications, and lifestyle factors affect bone mineral accrual. Appropriate reference values are essential for identification of children with bone deficits.

Objective: Our objective was to establish reference curves for bone mineral content (BMC) and density (BMD) in children.

Design and Setting: The Bone Mineral Density in Childhood Study is an ongoing longitudinal study in which measurements are obtained annually at five clinical centers in the United States.

Participants: Participants included 1554 healthy children (761 male, 793 female), ages 6–16 yr, of all ethnicities.

Main Outcome Measures: Scans of the whole body, lumbar spine, hip, and forearm were obtained using dual-energy x-ray absorptiometry. Percentile curves based on three annual measurements were generated using the LMS statistical procedure.

Results: BMC of the whole body and lumbar spine and BMD of the whole body, lumbar spine, total hip, femoral neck, and forearm are given for specific percentiles by sex, age, and race (Black *vs.* non-Black). BMC and BMD were higher for Blacks at all skeletal sites ($P < 0.0001$). BMC and BMD increased with age, and a plateau was not evident by age 16 (girls) or age 17 (boys). The variation in BMC and BMD also increased with age.

Conclusions: Age-, race-, and sex-specific reference curves can be used to help identify children with bone deficits and for monitoring changes in bone in response to chronic diseases or therapies. **(*J Clin Endocrinol Metab* 92: 2087–2099, 2007)**

THE 2000 NATIONAL INSTITUTES OF HEALTH Consensus Development Conference on Osteoporosis Prevention, Diagnosis, and Therapy identified bone mineral accretion during childhood as a critical determinant of osteoporosis risk later in life (1). Evidence suggests that lifestyle factors impact bone mineral accrual (2–4). Consequently, there is interest in monitoring the impact of behavioral modifications for maximizing bone mineral content (BMC) and density (BMD) during childhood and adolescence with the aim of preventing osteoporosis later in life.

For children with chronic disorders, identifying ways to increase bone mineral accrual is of particular importance because many have been found to have low BMC and BMD (5–8). Furthermore, medications such as anticonvulsants and corticosteroids have been found to decrease bone mineral accrual (6, 9–11). These reports have prompted recommendations for evaluation of BMC and BMD in children being considered for steroid therapy and for monitoring of response to therapy (12, 13).

Dual-energy x-ray absorptiometry (DXA) is, by far, the most widely used technique for measuring BMC and BMD in children due to its low cost, accessibility, and ease of use. To identify bone deficits, appropriate reference data are needed that adequately characterize the normal patterns of bone mineral accretion. The International Society of Clinical Densitometry (ISCD) recommends evaluation of BMC and BMD for a child's age (14). Although there are numerous publications describing DXA measures of BMC and BMD relative to age in healthy children (15–22), none have all of the attributes needed to serve as a reference. Important characteristics of a pediatric reference database include 1) the most current measurement technology with standardized data acquisition and 2) a well characterized, healthy, and ethnically diverse sample that is large enough to capture the normal variability in BMD. Additionally, the data should be analyzed using statistical methodology that adequately characterizes age-related trends and the distribution of values at different ages.

The purpose of this paper is to provide reference data for DXA measurements of BMC and BMD at multiple skeletal

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Abbreviations: BMC, Bone mineral content; BMD, bone mineral density; BMI, body mass index; DXA, dual-energy x-ray absorptiometry; FFQ, food frequency questionnaire; ISCD, International Society of Clinical Densitometry.

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sites that can be used for the identification of bone deficits in children and adolescents. Establishment of reference data for multiple skeletal sites will allow a comprehensive evaluation of bone status because some conditions or interventions may preferentially affect certain skeletal sites.

Subjects and Methods

Study population

Participants were recruited from five centers: Children's Hospital of Los Angeles (Los Angeles, CA), Cincinnati Children's Hospital Medical Center (Cincinnati, OH), Creighton University (Omaha, NE), Children's Hospital of Philadelphia (Philadelphia, PA), and Columbia University (New York, NY). Recruitment occurred from July 2002 to November 2003.

The sample was selected to reflect healthy, normally developing children in the United States from all major racial/ethnic groups. Girls ages 6–15 yr and boys ages 6–16 yr were recruited, with larger numbers of children recruited at ages where the greatest variation in pubertal stage was expected. The following inclusion criteria were used: residence in United States for at least 3 yr, school placement within 1 yr of that expected for age, full-term birth (≥37 wk gestation), birth weight greater than 2.3 kg, and no evidence of precocious or delayed puberty. For girls, normal puberty was defined as breast development beginning between 8 and 13 yr, menarche between 10 and 15 yr, and pubic hair present at 7 yr or older in African-American and Hispanic girls and 8 yr or older in non-Hispanic white or other ethnicities. For boys, the criteria were testes size of at least 4 ml between 9 and 14 yr and pubic hair development at 9 yr or older.

Exclusion criteria were height, weight, or body mass index (BMI; kg/m^2) less than third or more than 97th percentile (23); current or previous medical condition known to affect growth, maturation, physical activity, or nutritional status; medications known to affect growth, maturation, or bone mineral accrual such as steroids; secondary amenorrhea; history of long bone fractures (two or more fractures if age ≤ 10 yr; three or more fractures if age > 10 yr); indwelling hardware; abnormality of the skeleton or spine such as scoliosis 20 degrees or more, kyphosis, or skeletal dysplasia by history; current or previous pregnancy; same-sex sibling enrolled in the Bone Mineral Density in Childhood Study; and participation in a diet or exercise intervention study in the previous year.

Participants were screened by telephone questionnaire, and eligibility was confirmed by physical examination. Consent was obtained from each participant's parent or guardian, and assent was obtained from the participants. The protocol was approved by the institutional review boards of each clinical center. All of the following measurements were obtained at baseline and the first two annual follow-up visits.

Bone densitometry

DXA scans were performed using Hologic, Inc. (Bedford, MA) bone densitometers (QDR4500A, QDR4500W, and Delphi A models). Scans were performed on a single densitometer at each center. The software versions used for acquisition varied from version 11.1 to 12.3.

The following scans were performed according to manufacturer guidelines for subject positioning: whole body, posteroanterior lumbar spine (L1–L4, fast array), nondominant forearm, and left proximal femur (fast array). At study onset and in yr 3, the calibration of scanners was assessed by having all centers scan a single set of traveling phantoms that included the European Spine and Forearm Phantoms (QRM Inc., Möhrendorf, Germany) and the Hologic block, hip, and whole-body phantoms. The long-term calibration stability was monitored at each clinical site using two site-specific phantoms (Hologic anthropomorphic spine and whole-body phantoms) that were scanned weekly. The precision error for BMD and BMC were less than 1% for the spine phantom, and less than 2.5% for the whole-body phantom.

All scans were analyzed centrally by the DXA Core Laboratory (University of California, San Francisco) using Hologic software release 12.3. This software release has special features for pediatric scans. The spine, hip, and whole-body analyses use an automatic low-bone-density detection algorithm that increases the sensitivity of finding low-density bone. For hip and spine scans, two bone detection thresholds are applied to all scans. If low-density analysis yielded a bone area larger than 18% of the standard analysis, then the low-density results are reported. For whole-body scans, the bone detection threshold's sensitivity is continuously adjusted to be more sensitive as total body mass decreases from 40 to 8 kg. Outside this range, the bone edge sensitivities are constant with the most sensitive setting at 8 kg.

Descriptive measures

Height and weight measurements were obtained with participants dressed in examination gowns or lightweight clothing, without shoes. Weight was measured on a digital scale, and height was measured using a stadiometer. Z-scores for height, weight, and BMI were calculated using the Centers for Disease Control 2000 growth charts.

Ethnicity (Hispanic/Latino *vs.* non-Hispanic/Latino) and race were elicited by questionnaire using National Institutes of Health and the U.S. Bureau of the Census classifications.

Pubertal stage was determined by physical examination performed by a physician or nurse practitioner. The stage of pubic hair, breast development (girls), and testicular volume by orchidometer (boys) were evaluated using the criteria of Tanner (24).

Dietary calcium intake was estimated by a semiquantitative food frequency questionnaire (FFQ) developed by Block Dietary Data Systems (Berkeley, CA). The FFQ asked about the frequency of intake in the last week and serving sizes of forty-five food and beverage items. Parents of young children completed or helped the participant complete the FFQ, whereas adolescents (>13 yr old) were more likely to fill out the FFQ themselves. Dietary calcium intake was calculated from the questionnaire using an automated computer analysis program by Block Dietary Data Systems.

Statistical analysis

The LMS statistical method (25) was used to construct reference curves for BMC and BMD *vs.* age. Sex- and race-specific curves were constructed for each measurement site. The LMS technique estimates three parameters: median (M), SD (S), and power in the Box-Cox transformation (L). These three parameters vary as a function of age. Once these parameters are estimated, then centile curves can be constructed using the formula 1: BMC or BMD centile = $M\ (1 + LSZ)^{1/L}$, where Z is the Z-score that corresponds to a given percentile. The age-specific parameter estimates (L, M, and S) can be entered into the equation to calculate the BMD value for that percentile at each age.

A Z-score for an individual DXA measurement also can be calculated using the age-specific L, M, and S parameters. The formula used to obtain the Z-score is formula 2: $Z = [(X/M)^L) - 1]/LS$, where X is the physical measurement (*e.g.* whole-body BMD).

Generation of the LMS curves was performed using the LMS Professional software version 1.16 (University College London, London, UK). Worm plots were used to assess goodness of fit (26). In addition, we checked the fit of the curves by overlaying empirical distributions with the centile curves. Data from the baseline visit to the yr 2 visit (boys, 6–18 yr; girls, 6–17 yr) were used to generate the centile curves. The fit at the youngest and oldest ages was poor due to insufficient sample sizes; therefore, curves are presented for boys 7–17 yr and girls 7–16 yr of age. All other summary statistics and analyses were performed using SAS version 8 (SAS Institute, Cary, NC). To assess the need for separate curves for each race/ethnic group, a mixed model was used to test for racial differences in mean BMC and BMD. BMC and BMD were modeled as polynomial functions of age. Race and age-race interactions were tested to determine whether there were significant differences across the race/ethnic groups. A general linear model was used to make racial comparisons of the mean height, weight, and BMI Z-scores and dietary calcium intake across the sex and age categories.

Results

Study population characteristics

The number of children screened was 2889, of which 1335 (46%) were ineligible. The leading reason for exclusion (30%) was height, weight, or BMI less than the third percentile or

TABLE 1. Descriptive characteristics of BMD in Childhood Study participants at baseline

	Boys			Girls		
	6–8 yr	9–12 yr	13–16 yr	6–8 yr	9–12 yr	13–15 yr
Non-Black						
Overall n:FFQ n	174:173	220:219	186:186	198:198	236:236	169:167
Height-for-age Z-score[a]	0.04 ± 0.81[b]	0.08 ± 0.77	0.16 ± 0.79	0.02 ± 0.80	0.21 ± 0.85	0.04 ± 0.81
Weight-for-age Z-score[a]	0.17 ± 0.79	0.15 ± 0.81	0.45 ± 0.78	0.17 ± 0.80	0.24 ± 0.84	0.44 ± 0.73
BMI-for-age Z-score[a]	0.24 ± 0.75	0.19 ± 0.91	0.36 ± 0.82	0.22 ± 0.83	0.27 ± 0.84	0.46 ± 0.73
Dietary calcium intake (mg/d)[a]	1021 ± 506	1098 ± 603	1119 ± 712	849 ± 429	885 ± 527	875 ± 556
Black						
Overall n:FFQ n	48:47	71:71	62:62	57:56	79:78	54:54
Height-for-age Z-score	0.20 ± 0.78	0.45 ± 0.81	0.19 ± 0.78	0.17 ± 0.84	0.43 ± 0.84	0.07 ± 0.74
Weight-for-age Z-score	0.41 ± 0.86	0.50 ± 0.79	0.48 ± 0.79	0.31 ± 0.77	0.56 ± 0.71	0.66 ± 0.69
BMI-for-age Z-score	0.42 ± 0.92	0.44 ± 0.82	0.39 ± 0.84	0.31 ± 0.78	0.53 ± 0.79	0.67 ± 0.81
Dietary calcium intake (mg/d)	896 ± 456	820 ± 560	823 ± 663	783 ± 367	704 ± 530	605 ± 360

[a] Non-Black *vs.* Black, $P < 0.001$.
[b] Mean ± SD.

greater than the 97th percentile for age. Low birth weight/prematurity, corticosteroid use, other medication use, parent refusal to schedule, and no-show at baseline visit each accounted for approximately 10% of the ineligible children. Less than 2% of children were excluded for history of fractures.

The sample consisted of 761 boys and 793 girls. When categorized by mother's stated racial/ethnic group, the distribution was 49.2% white non-Hispanic, 24.2% Black non-Hispanic, 15.9% Hispanic, 7.8% Asian/Pacific Islander, and 2.9% American Indian, mixed race, or unknown. For all results presented here, the children were categorized as either Black or non-Black based on the parent's report of the child's race.

Of the 1554 children enrolled, 1477 returned for yr 1 and 1443 returned for yr 2 measurements. Participants were not excluded if during the follow-up period they developed medical conditions (n = 33) or used medications (n = 184) that would have precluded them from enrollment initially.

At enrollment, the height, weight, and BMI Z-scores were significantly greater than zero (Table 1), signaling that the children were tall and heavy relative to the Centers for Disease Control reference curves as is typical of U.S. children (27). Z-scores for height ($P = 0.004$), weight ($P < 0.0001$), and BMI ($P = 0.003$) were greater for Black children compared with non-Black children.

Sexual maturation at enrollment by race and sex is given in Table 2. Prepubertal was defined as Tanner breast stage 1 for girls and as testes size less than 4 ml for boys. At enrollment, 681 children were prepubertal (331 girls) and 873 were pubertal (462 girls). The mean ages of Black girls who were at breast stages 3–5 were younger than non-Black girls in the same breast stage ($P < 0.01$). Among boys, mean ages for pubertal stages 1–5 did not differ between Black and non-Black participants.

FFQ data for estimation of calcium intake was available from 1547 of the 1554 participants at enrollment. The mean calcium intakes by age, sex, and race/ethnicity groups are given in Table 1. The calcium intake was greater for boys than for girls ($P < 0.0001$) and was greater for non-Blacks than for Blacks ($P < 0.0001$).

DXA

The analysis of DXA scans of the traveling set of phantoms revealed markedly elevated BMC (~15%) and BMD (~7%) values at one clinic. This site's calibration was adjusted back to its factory setting, and all scans were reanalyzed. Afterward, all study sites had BMC and BMD values that agreed within ±0.6, 2, and 3% for the spine, hip, and forearm scans, respectively, but only within ±4 and 6% for the whole-body BMC and BMD, respectively. It is important to note that the participant's BMD values were not adjusted for these remaining calibration differences before pooling the data across centers so

TABLE 2. Chronological age by sex, pubertal stage, and racial group at baseline

Pubertal stage[a]	Non-Black		Black		*P*
	n	Chronological age[b]	n	Chronological age[b]	
Girls (breast)					
1	269	8.0 ± 1.5 (6.0–12.8)	62	7.6 ± 1.2 (6.0–10.7)	0.02
2	68	10.7 ± 1.0 (8.0–13.7)	19	10.3 ± 1.2 (8.8–13.0)	0.13
3	80	12.0 ± 1.4 (9.5–15.5)	20	11.0 ± 0.9 (9.5–12.9)	<0.001
4	92	13.7 ± 1.4 (10.2–16.0)	35	12.5 ± 1.3 (10.3–15.8)	<0.001
5	94	14.5 ± 1.1 (11.4–16.0)	54	13.9 ± 1.3 (10.2–16.0)	<0.01
Boys (testes)					
1 (≤3 ml)	273	8.3 ± 1.7 (6.0–12.1)	77	8.6 ± 1.7 (6.0–13.7)	0.18
2 (4–6 ml)	90	11.4 ± 1.3 (9.2–14.7)	29	11.4 ± 1.2 (9.5–14.1)	0.87
3 (8–10 ml)	44	12.7 ± 1.3 (9.8–14.9)	17	13.2 ± 1.5 (10.4–16.8)	0.19
4 (12–15 ml)	56	13.8 ± 1.2 (11.1–16.8)	25	14.0 ± 1.4 (11.3–16.8)	0.58
5 (>15 ml)	117	15.2 ± 1.0 (11.8–17.0)	33	15.0 ± 1.3 (12.3–17.0)	0.39

[a] Pubertal stages based on Tanner stages of breast development for girls and testes size for boys.
[b] Mean ± SD (range).

TABLE 3. Lumbar spine BMD: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (135)	0.474	0.111	0.423	0.455	0.527	0.605	0.643	7 (147)	−0.616	0.116	0.431	0.458	0.528	0.618	0.668
8 (158)	0.477	0.112	0.442	0.476	0.552	0.634	0.675	8 (177)	−0.524	0.117	0.449	0.479	0.553	0.646	0.698
9 (132)	0.484	0.113	0.459	0.494	0.574	0.661	0.703	9 (152)	−0.438	0.118	0.467	0.499	0.578	0.676	0.730
10 (157)	0.519	0.114	0.474	0.511	0.595	0.685	0.729	10 (174)	−0.314	0.124	0.487	0.523	0.610	0.718	0.777
11 (174)	0.616	0.116	0.489	0.529	0.618	0.712	0.758	11 (178)	−0.048	0.140	0.508	0.552	0.660	0.791	0.861
12 (158)	0.872	0.118	0.510	0.555	0.653	0.753	0.800	12 (175)	0.443	0.152	0.546	0.605	0.742	0.894	0.971
13 (131)	1.25	0.121	0.540	0.595	0.707	0.815	0.865	13 (159)	0.870	0.137	0.622	0.688	0.833	0.981	1.051
14 (157)	1.28	0.125	0.593	0.655	0.784	0.907	0.962	14 (157)	0.781	0.119	0.712	0.774	0.910	1.052	1.119
15 (150)	0.692	0.126	0.674	0.736	0.873	1.018	1.087	15 (164)	0.582	0.110	0.769	0.828	0.958	1.097	1.164
16 (144)	0.213	0.125	0.746	0.807	0.950	1.112	1.194	16 (105)	0.471	0.105	0.799	0.855	0.982	1.118	1.185
17 (70)	−0.211	0.123	0.800	0.859	1.003	1.179	1.273								
Black															
7 (35)	2.79	0.103	0.415	0.466	0.549	0.615	0.642	7 (37)	0.814	0.118	0.446	0.485	0.570	0.657	0.698
8 (44)	2.37	0.110	0.439	0.491	0.583	0.658	0.690	8 (50)	0.759	0.118	0.463	0.502	0.590	0.681	0.724
9 (47)	2.05	0.114	0.458	0.511	0.608	0.691	0.727	9 (45)	0.685	0.118	0.486	0.527	0.618	0.714	0.760
10 (45)	1.79	0.118	0.473	0.526	0.628	0.717	0.757	10 (55)	0.576	0.118	0.524	0.567	0.664	0.768	0.818
11 (49)	1.47	0.122	0.492	0.545	0.651	0.750	0.794	11 (48)	0.433	0.118	0.584	0.630	0.737	0.854	0.912
12 (46)	0.995	0.128	0.526	0.579	0.692	0.806	0.859	12 (61)	0.269	0.118	0.659	0.710	0.829	0.962	1.029
13 (52)	0.490	0.134	0.580	0.634	0.758	0.894	0.961	13 (58)	0.113	0.119	0.727	0.781	0.911	1.059	1.135
14 (57)	0.158	0.135	0.649	0.706	0.841	0.998	1.079	14 (63)	−0.021	0.119	0.777	0.834	0.971	1.131	1.214
15 (44)	−0.021	0.132	0.722	0.781	0.924	1.095	1.185	15 (49)	−0.127	0.119	0.811	0.870	1.011	1.179	1.268
16 (44)	−0.137	0.127	0.775	0.835	0.981	1.157	1.252	16 (26)	−0.212	0.119	0.836	0.895	1.040	1.214	1.307
17 (21)	−0.231	0.124	0.806	0.866	1.012	1.19	1.287								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

that the sample variances would include variability due to expected differences in site-to-site calibration.

Information on BMD of the lumbar spine, total hip, femoral neck, one third radius, and the whole body, and BMC of the whole body and lumbar spine are given in Tables 3–9 for boys 7–17 yr and girls 7–16 yr. Specific percentiles (3rd, 10th, 50th, 90th, and 97th) for each sex and race/ethnicity group are presented for exact ages. Percentile values should be interpolated for children who are between birthdays. For example, a child who is 10.3 yr of age will have a percentile value that is 30% of the distance between the values for a child who is 10.0 yr and one who is 11.0 yr. BMC and BMD at all skeletal sites were higher for Blacks compared with the other ethnic groups ($P < 0.001$), resulting in the need to estimate separate percentile curves. Among non-Black children, there were no other race/ethnic-specific differences in BMC or BMD that were consistent across skeletal sites for males and females. The LMS parameters also are given in Tables 3–9 so that the exact Z-scores can be calculated using formula 2. Skewness in the distributions, as indicated by L-values differing from 1, was evident for most measures.

TABLE 4. Total hip BMD: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (136)	1.636	0.102	0.516	0.561	0.651	0.733	0.769	7 (147)	0.231	0.094	0.504	0.534	0.603	0.678	0.716
8 (158)	1.270	0.103	0.545	0.589	0.681	0.770	0.811	8 (175)	0.075	0.096	0.523	0.554	0.627	0.709	0.750
9 (132)	0.949	0.103	0.572	0.615	0.709	0.803	0.847	9 (152)	−0.177	0.098	0.543	0.575	0.651	0.739	0.785
10 (156)	0.682	0.102	0.597	0.640	0.734	0.832	0.879	10 (175)	−0.597	0.103	0.568	0.601	0.682	0.782	0.837
11 (174)	0.451	0.101	0.623	0.666	0.761	0.863	0.913	11 (178)	−0.877	0.113	0.598	0.634	0.727	0.848	0.919
12 (158)	0.258	0.102	0.651	0.694	0.792	0.901	0.955	12 (176)	−0.313	0.124	0.634	0.680	0.794	0.935	1.012
13 (131)	0.181	0.109	0.680	0.727	0.838	0.961	1.024	13 (158)	0.507	0.126	0.675	0.734	0.868	1.013	1.085
14 (156)	0.353	0.118	0.717	0.773	0.904	1.048	1.120	14 (157)	0.687	0.122	0.718	0.781	0.921	1.068	1.139
15 (150)	0.616	0.123	0.766	0.832	0.982	1.142	1.219	15 (163)	0.714	0.118	0.744	0.808	0.948	1.095	1.165
16 (142)	0.761	0.124	0.806	0.879	1.042	1.211	1.291	16 (105)	0.737	0.116	0.758	0.821	0.962	1.108	1.178
17 (70)	0.789	0.124	0.832	0.909	1.078	1.253	1.336								
Black															
7 (35)	2.846	0.093	0.566	0.623	0.720	0.798	0.830	7 (37)	−0.634	0.091	0.570	0.599	0.670	0.757	0.804
8 (44)	2.599	0.097	0.585	0.644	0.748	0.833	0.868	8 (50)	−0.634	0.093	0.582	0.613	0.688	0.779	0.829
9 (47)	2.369	0.100	0.601	0.663	0.772	0.864	0.903	9 (45)	−0.634	0.097	0.599	0.631	0.712	0.810	0.863
10 (45)	2.125	0.104	0.619	0.681	0.798	0.897	0.940	10 (55)	−0.634	0.102	0.624	0.659	0.748	0.857	0.917
11 (49)	1.822	0.110	0.641	0.705	0.829	0.940	0.988	11 (48)	−0.634	0.108	0.667	0.707	0.807	0.933	1.004
12 (46)	1.432	0.117	0.672	0.739	0.874	1.001	1.058	12 (61)	−0.634	0.112	0.722	0.767	0.879	1.022	1.102
13 (52)	0.971	0.126	0.713	0.783	0.933	1.083	1.154	13 (58)	−0.634	0.114	0.766	0.814	0.936	1.091	1.178
14 (55)	0.480	0.132	0.765	0.836	0.996	1.172	1.259	14 (63)	−0.634	0.119	0.791	0.843	0.975	1.145	1.242
15 (43)	0.005	0.132	0.822	0.889	1.053	1.247	1.349	15 (49)	−0.634	0.125	0.800	0.855	0.995	1.178	1.283
16 (42)	−0.425	0.129	0.871	0.935	1.098	1.304	1.419	16 (26)	−0.634	0.127	0.803	0.860	1.004	1.193	1.302
17 (21)	−0.808	0.127	0.909	0.971	1.132	1.348	1.477								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

TABLE 5. Femoral neck BMD: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (136)	0.773	0.104	0.494	0.531	0.611	0.694	0.733	7 (147)	0.059	0.092	0.476	0.504	0.567	0.638	0.674
8 (158)	0.584	0.105	0.520	0.557	0.641	0.729	0.772	8 (175)	−0.082	0.095	0.494	0.523	0.591	0.668	0.708
9 (132)	0.427	0.105	0.542	0.580	0.667	0.760	0.806	9 (152)	−0.253	0.099	0.512	0.542	0.614	0.698	0.743
10 (156)	0.303	0.106	0.562	0.601	0.690	0.788	0.837	10 (175)	−0.426	0.103	0.533	0.565	0.643	0.736	0.787
11 (174)	0.202	0.107	0.580	0.620	0.712	0.816	0.868	11 (178)	−0.353	0.109	0.560	0.595	0.682	0.786	0.843
12 (158)	0.120	0.109	0.600	0.641	0.737	0.846	0.902	12 (176)	0.313	0.115	0.588	0.633	0.736	0.850	0.907
13 (131)	0.070	0.112	0.625	0.669	0.773	0.892	0.953	13 (158)	0.804	0.122	0.615	0.670	0.792	0.917	0.977
14 (156)	0.116	0.118	0.658	0.707	0.824	0.956	1.025	14 (157)	0.726	0.127	0.641	0.701	0.834	0.974	1.041
15 (150)	0.265	0.125	0.695	0.752	0.886	1.036	1.113	15 (163)	0.687	0.132	0.656	0.720	0.861	1.010	1.082
16 (142)	0.426	0.133	0.721	0.787	0.939	1.107	1.191	16 (105)	0.753	0.134	0.662	0.729	0.877	1.031	1.105
17 (70)	0.549	0.140	0.736	0.810	0.978	1.161	1.251								
Black															
7 (35)	0.664	0.113	0.533	0.576	0.670	0.770	0.818	7 (37)	−1.067	0.098	0.520	0.547	0.615	0.703	0.754
8 (44)	1.068	0.115	0.548	0.597	0.701	0.805	0.853	8 (50)	−0.963	0.102	0.537	0.566	0.641	0.737	0.792
9 (47)	1.433	0.118	0.558	0.615	0.728	0.835	0.883	9 (45)	−0.840	0.108	0.558	0.590	0.673	0.779	0.84
10 (45)	1.734	0.120	0.567	0.631	0.754	0.865	0.913	10 (55)	−0.693	0.114	0.584	0.621	0.714	0.833	0.901
11 (49)	1.938	0.122	0.578	0.651	0.785	0.900	0.949	11 (48)	−0.524	0.122	0.618	0.660	0.767	0.903	0.979
12 (46)	1.923	0.125	0.602	0.680	0.824	0.948	1.001	12 (61)	−0.352	0.130	0.652	0.701	0.823	0.977	1.062
13 (52)	1.575	0.129	0.642	0.720	0.872	1.009	1.070	13 (58)	−0.196	0.136	0.677	0.733	0.870	1.040	1.132
14 (55)	0.993	0.133	0.692	0.765	0.922	1.078	1.152	14 (63)	−0.070	0.142	0.693	0.754	0.904	1.085	1.183
15 (43)	0.422	0.136	0.738	0.807	0.968	1.145	1.234	15 (49)	0.019	0.146	0.701	0.766	0.924	1.113	1.215
16 (42)	0.047	0.139	0.773	0.841	1.006	1.202	1.306	16 (26)	0.075	0.149	0.705	0.772	0.935	1.130	1.233
17 (21)	−0.156	0.142	0.799	0.867	1.038	1.249	1.365								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

Graphs of whole-body and lumbar spine BMC and BMD by age are given in Fig. 1 for males and Fig. 2 for females. Graphs of the total hip, femoral neck, and one third radius BMD *vs.* age are given in Fig. 3 for males and Fig. 4 for females. The empirical percentile values for each age group are plotted on the curves allowing for a visual inspection of the fit of the data. It is evident that BMC and BMD are still increasing at age 16 yr in girls and at age 17 yr in boys. The divergence in the percentiles and the increasing S-values (Tables 3–9), indicating greater variability, also are evident as children age.

TABLE 6. One third radius BMD: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (129)	0.718	0.072	0.393	0.411	0.452	0.495	0.515	7 (135)	0.842	0.072	0.386	0.405	0.446	0.488	0.508
8 (151)	0.527	0.071	0.411	0.430	0.472	0.516	0.538	8 (172)	0.386	0.075	0.405	0.425	0.469	0.515	0.538
9 (129)	0.379	0.071	0.428	0.447	0.491	0.536	0.559	9 (149)	0.409	0.077	0.418	0.439	0.485	0.534	0.558
10 (154)	0.268	0.071	0.443	0.463	0.507	0.555	0.579	10 (171)	0.804	0.078	0.431	0.454	0.504	0.555	0.579
11 (170)	0.167	0.072	0.457	0.478	0.525	0.575	0.600	11 (176)	1.279	0.081	0.449	0.476	0.532	0.586	0.611
12 (154)	0.075	0.075	0.474	0.496	0.547	0.602	0.629	12 (173)	1.661	0.082	0.478	0.509	0.571	0.630	0.656
13 (130)	0.039	0.081	0.495	0.520	0.577	0.640	0.671	13 (158)	1.942	0.079	0.512	0.545	0.610	0.670	0.696
14 (156)	0.059	0.086	0.523	0.550	0.615	0.686	0.721	14 (158)	1.570	0.074	0.545	0.575	0.637	0.696	0.723
15 (150)	0.071	0.087	0.558	0.588	0.658	0.735	0.774	15 (164)	1.177	0.069	0.569	0.596	0.655	0.713	0.740
16 (144)	0.091	0.083	0.599	0.630	0.701	0.779	0.818	16 (105)	0.985	0.066	0.585	0.611	0.668	0.724	0.751
17 (68)	0.127	0.075	0.637	0.667	0.735	0.809	0.845								
Black															
7 (34)	0.982	0.081	0.408	0.431	0.481	0.531	0.555	7 (37)	1.308	0.069	0.414	0.434	0.477	0.518	0.537
8 (43)	0.634	0.082	0.434	0.458	0.511	0.565	0.592	8 (49)	1.189	0.072	0.426	0.448	0.494	0.540	0.561
9 (47)	0.415	0.083	0.455	0.480	0.535	0.594	0.622	9 (45)	1.040	0.075	0.439	0.462	0.511	0.560	0.583
10 (44)	0.350	0.084	0.471	0.497	0.555	0.617	0.647	10 (54)	0.805	0.075	0.460	0.484	0.535	0.587	0.612
11 (49)	0.412	0.086	0.485	0.512	0.573	0.638	0.669	11 (48)	0.506	0.075	0.492	0.516	0.570	0.626	0.653
12 (46)	0.597	0.087	0.499	0.528	0.593	0.66	0.693	12 (61)	0.469	0.075	0.528	0.553	0.610	0.670	0.699
13 (52)	0.969	0.088	0.517	0.549	0.619	0.688	0.721	13 (58)	0.816	0.073	0.556	0.584	0.643	0.704	0.733
14 (57)	1.556	0.087	0.542	0.579	0.654	0.724	0.756	14 (63)	1.326	0.069	0.578	0.607	0.667	0.725	0.752
15 (44)	2.245	0.083	0.572	0.614	0.693	0.762	0.792	15 (49)	1.808	0.065	0.594	0.623	0.682	0.738	0.763
16 (43)	2.914	0.077	0.602	0.647	0.727	0.793	0.821	16 (26)	2.213	0.062	0.606	0.636	0.694	0.747	0.770
17 (21)	3.484	0.071	0.629	0.675	0.753	0.816	0.841								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

TABLE 7. Whole-body BMD: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (134)	−0.433	0.070	0.636	0.662	0.723	0.793	0.828	7 (146)	−1.118	0.072	0.612	0.636	0.695	0.766	0.805
8 (154)	−0.471	0.068	0.673	0.699	0.762	0.833	0.870	8 (173)	−0.952	0.072	0.644	0.670	0.732	0.806	0.846
9 (128)	−0.506	0.066	0.706	0.733	0.797	0.869	0.906	9 (150)	−0.792	0.072	0.674	0.702	0.767	0.844	0.884
10 (156)	−0.538	0.065	0.735	0.762	0.827	0.900	0.938	10 (173)	−0.618	0.072	0.706	0.736	0.805	0.885	0.927
11 (172)	−0.568	0.064	0.761	0.789	0.855	0.929	0.968	11 (176)	−0.414	0.074	0.740	0.772	0.847	0.933	0.977
12 (156)	−0.602	0.064	0.789	0.818	0.886	0.964	1.004	12 (171)	−0.154	0.077	0.780	0.816	0.900	0.994	1.042
13 (130)	−0.645	0.066	0.822	0.853	0.926	1.010	1.053	13 (157)	0.148	0.078	0.830	0.871	0.963	1.064	1.113
14 (156)	−0.696	0.070	0.861	0.896	0.977	1.072	1.122	14 (156)	0.433	0.076	0.882	0.925	1.021	1.123	1.173
15 (151)	−0.755	0.075	0.907	0.946	1.038	1.146	1.205	15 (161)	0.638	0.072	0.919	0.963	1.059	1.159	1.207
16 (140)	−0.815	0.079	0.954	0.996	1.098	1.221	1.287	16 (105)	0.754	0.070	0.939	0.983	1.079	1.177	1.224
17 (70)	−0.872	0.082	0.996	1.041	1.151	1.285	1.358								
Black															
7 (35)	3.756	0.064	0.664	0.706	0.778	0.835	0.859	7 (37)	2.402	0.062	0.657	0.690	0.753	0.810	0.834
8 (43)	3.241	0.065	0.701	0.744	0.820	0.883	0.910	8 (49)	2.012	0.063	0.687	0.720	0.787	0.849	0.876
9 (46)	2.780	0.066	0.736	0.779	0.857	0.925	0.954	9 (45)	1.635	0.065	0.713	0.747	0.817	0.884	0.914
10 (45)	2.364	0.066	0.767	0.809	0.890	0.961	0.992	10 (53)	1.164	0.067	0.746	0.781	0.855	0.928	0.962
11 (49)	1.979	0.067	0.794	0.835	0.918	0.994	1.027	11 (47)	0.525	0.070	0.796	0.832	0.912	0.996	1.036
12 (46)	1.573	0.069	0.819	0.861	0.947	1.029	1.066	12 (58)	−0.174	0.073	0.851	0.889	0.975	1.072	1.121
13 (51)	1.079	0.075	0.846	0.891	0.987	1.082	1.126	13 (53)	−0.786	0.076	0.895	0.933	1.025	1.133	1.192
14 (55)	0.623	0.087	0.878	0.929	1.043	1.161	1.218	14 (58)	−1.293	0.078	0.932	0.970	1.066	1.186	1.254
15 (45)	0.375	0.094	0.921	0.978	1.107	1.246	1.314	15 (47)	−1.677	0.080	0.960	0.999	1.098	1.228	1.304
16 (43)	0.242	0.091	0.975	1.032	1.162	1.304	1.374	16 (22)	−1.918	0.081	0.977	1.016	1.117	1.253	1.336
17 (19)	0.117	0.082	1.027	1.080	1.201	1.334	1.400								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

Discussion

For many years, clinicians and researchers concerned with bone health of children have recognized the need for appropriate pediatric BMC and BMD reference data. We have provided reference values for BMC and BMD according to age, sex, and race that can be used to aid the identification of children that have impaired bone mineral accrual. These are the first ethnic-specific reference values for BMC and BMD from a large multicentered sample of children gathered with a standardized protocol, using LMS modeling to create reference curves. Importantly, this is the first study that is large enough in scope to detect that the variability in BMC

TABLE 8. Whole-body BMC: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (134)	−0.404	0.111	682.8	726.3	833.6	964.6	1035.8	7 (146)	−0.806	0.112	658.6	698.3	799.5	930.6	1006.1
8 (154)	−0.377	0.110	760.0	808.7	928.3	1073.6	1152.4	8 (173)	−0.813	0.111	729.3	773.1	884.7	1029.4	1112.7
9 (128)	−0.353	0.110	835.8	889.4	1020.6	1179.4	1265.2	9 (150)	−0.822	0.112	798.4	846.5	969.0	1128.3	1220.2
10 (156)	−0.33	0.110	908.0	966.3	1108.9	1280.9	1373.6	10 (173)	−0.803	0.117	872.7	927.8	1069.3	1255.2	1363.3
11 (172)	−0.302	0.111	985.7	1050.0	1207.1	1396.2	1497.8	11 (176)	−0.642	0.136	954.4	1025.4	1210.2	1456.6	1601.6
12 (156)	−0.259	0.116	1085.2	1159.6	1341.5	1560.9	1678.9	12 (171)	−0.141	0.158	1056.3	1157.2	1412.1	1733.1	1911.2
13 (130)	−0.192	0.127	1214.3	1306.8	1534.4	1810.8	1960.2	13 (157)	0.514	0.157	1192.1	1327.5	1640.9	1986.4	2158.9
14 (156)	−0.121	0.141	1382.9	1501.4	1795.0	2154.6	2349.9	14 (156)	0.884	0.141	1352.9	1503.0	1829.7	2163.3	2321.4
15 (151)	−0.104	0.146	1592.4	1734.1	2086.1	2518.7	2754.2	15 (161)	1.042	0.127	1483.7	1633.9	1953.1	2270.0	2417.6
16 (140)	−0.158	0.143	1796.3	1951.6	2339.1	2818.5	3081.2	16 (105)	1.140	0.118	1569.7	1716.6	2025.0	2326.9	2466.2
17 (70)	−0.256	0.139	1964.6	2126.3	2532.3	3040.5	3322.0								
Black															
7 (35)	2.266	0.092	732.3	794.9	911.2	1011.2	1053.9	7 (37)	−0.860	0.099	743.2	783.2	883.7	1011.2	1083.2
8 (43)	1.980	0.099	803.6	876.2	1014.5	1136.4	1189.2	8 (49)	−0.793	0.105	798.3	844.1	959.5	1106.8	1190.3
9 (46)	1.690	0.107	874.4	957.0	1119.0	1266.2	1331.1	9 (45)	−0.671	0.111	856.3	909.0	1041.8	1210.4	1305.6
10 (45)	1.383	0.116	948.4	1041.6	1230.9	1409.7	1490.3	10 (53)	−0.303	0.119	940.5	1006.1	1167.7	1364.8	1472.0
11 (49)	1.039	0.128	1034.3	1139.5	1363.2	1585.6	1689.1	11 (47)	0.394	0.126	1076.7	1168.3	1379.6	1612.5	1729.1
12 (46)	0.654	0.141	1142.9	1262.2	1530.8	1816.9	1956.4	12 (58)	0.646	0.127	1252.9	1367.9	1625.4	1898.3	2030.9
13 (51)	0.272	0.156	1283.4	1418.3	1741.1	2114.4	2307.5	13 (53)	0.449	0.127	1412.3	1535.6	1818.5	2128.0	2282.0
14 (55)	−0.019	0.164	1456.6	1606.7	1983.0	2449.4	2704.4	14 (58)	0.106	0.129	1538.2	1664.8	1967.1	2317.6	2499.9
15 (45)	−0.150	0.164	1649.2	1812.4	2228.1	2757.1	3053.2	15 (47)	−0.131	0.132	1621.5	1751.3	2070.3	2456.6	2664.7
16 (43)	−0.157	0.154	1848.4	2019.7	2451.5	2993.9	3294.5	16 (22)	−0.266	0.135	1672.7	1805.4	2137.0	2549.8	2777.4
17 (19)	−0.120	0.139	2046.2	2219.3	2647.5	3170.3	3453.7								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

TABLE 9. Lumbar spine BMC: LMS values and selected modeled percentiles by sex, race, and age

Male								Female							
Age, yr (n)	LMS parameters and modeled percentiles							Age, yr (n)	LMS parameters and modeled percentiles						
	L	S	3rd	10th	M 50th	90th	97th		L	S	3rd	10th	M 50th	90th	97th
Non-Black															
7 (135)	0.259	0.146	14.1	15.4	18.7	22.4	24.3	7 (147)	−0.584	0.146	13.7	14.8	17.6	21.5	23.8
8 (158)	0.261	0.146	15.6	17.1	20.7	24.9	27.0	8 (177)	−0.553	0.153	14.9	16.2	19.5	23.9	26.6
9 (132)	0.263	0.147	17.1	18.7	22.7	27.3	29.7	9 (152)	−0.515	0.159	16.2	17.6	21.4	26.5	29.6
10 (157)	0.265	0.148	18.5	20.3	24.7	29.7	32.3	10 (174)	−0.450	0.168	17.7	19.4	23.8	29.8	33.5
11 (174)	0.266	0.150	19.9	21.9	26.7	32.2	35.0	11 (178)	−0.295	0.182	20.0	22.1	27.7	35.2	39.7
12 (158)	0.269	0.158	21.8	24.1	29.7	36.2	39.5	12 (175)	0.010	0.195	23.5	26.5	34.0	43.6	49.0
13 (131)	0.281	0.178	24.6	27.6	34.9	43.5	48.0	13 (159)	0.326	0.196	28.2	32.2	41.8	53.2	59.2
14 (157)	0.318	0.198	28.6	32.6	42.5	54.3	60.5	14 (157)	0.471	0.184	33.0	37.5	48.1	60.2	66.4
15 (150)	0.374	0.194	35.2	40.1	52.1	66.0	73.2	15 (164)	0.510	0.172	36.5	41.2	52.0	64.0	70.1
16 (144)	0.415	0.179	42.0	47.5	60.4	75.2	82.8	16 (105)	0.522	0.162	38.8	43.4	54.1	66.0	71.9
17 (70)	0.417	0.173	46.6	52.4	66.1	81.8	89.8								
Black															
7 (35)	1.039	0.143	14.1	15.8	19.3	22.9	24.5	7 (37)	−0.947	0.142	14.6	15.7	18.5	22.6	25.2
8 (44)	0.871	0.148	15.7	17.6	21.6	25.8	27.7	8 (50)	−0.785	0.149	15.5	16.7	20.0	24.5	27.4
9 (47)	0.673	0.152	17.3	19.3	23.8	28.5	30.9	9 (45)	−0.556	0.159	16.7	18.2	22.0	27.3	30.5
10 (45)	0.445	0.157	18.8	20.9	25.8	31.2	34	10 (55)	−0.243	0.174	18.7	20.6	25.6	32.2	36.0
11 (49)	0.139	0.163	20.6	22.8	28.2	34.7	38.1	11 (48)	0.017	0.188	22.2	24.9	31.7	40.3	45.0
12 (46)	−0.279	0.174	23.3	25.7	31.9	40.2	45.0	12 (61)	0.102	0.187	27.5	30.8	39.3	49.8	55.5
13 (52)	−0.503	0.190	27.1	30.0	37.7	48.9	55.9	13 (58)	0.203	0.179	32.4	36.3	45.9	57.5	63.6
14 (57)	−0.245	0.203	31.8	35.6	45.8	59.9	68.4	14 (63)	0.152	0.175	36.3	40.4	50.8	63.3	70.0
15 (44)	0.063	0.206	36.7	41.6	54.3	70.6	79.6	15 (49)	0.032	0.170	39.2	43.4	54.0	67.1	74.3
16 (44)	0.137	0.198	41.1	46.5	60.3	77.4	86.8	16 (26)	−0.072	0.165	41.4	45.6	56.2	69.6	77.0
17 (21)	0.065	0.189	44.5	49.9	63.8	81.6	90.7								

Percentile values should be interpolated for children who are between birthdays; n is the number of observations in that age category.

and BMD increase with age and that the values are not normally distributed. As a consequence, special statistical techniques are required for calculation of Z-scores, and it is inappropriate to simply use the mean and SD to do so for these measures. The LMS modeling approach provides greater accuracy in describing reference ranges, particularly the upper and lower ends of the distribution. Accurate identification of the lower ends of the range has particularly important clinical care consequences for identification of children with impaired BMC and BMD.

The sample was selected to represent healthy children from multiple geographic locations in the United States. It is recognized that physical activity, dietary intake, and heredity also affect BMD, but these were not included as criteria for subject selection. Thus, the data presented reflect reference values for a healthy population but do not necessarily represent optimal values. The height, weight, BMI, and estimated calcium intake of our sample are similar to that of children in the 1999–2000 National Health and Nutrition Examination Survey, suggesting that our sample is reflective of children in the United States (27, 28).

Several trends in these reference data merit comment. First, it is evident that girls at age 16 yr and boys at age 17 yr are still gaining BMC and BMD at all skeletal sites measured. The rapid rate of bone mineral accrual is particularly evident in boys. There also is an increase in the variability of BMC and BMD with age, and the distance between percentile curves widens markedly. At all ages, BMC of the whole body and BMD of the whole body, hip, and radius are greater for Blacks compared with non-Blacks, consistent with previous studies (15, 29, 30). In our cohort, Black girls had more rapid pubertal development, and Black girls and boys had higher weight and height, which may explain part of the observed race differences.

The findings presented here can be used to determine a child's percentile rank for BMC and BMD, similar to the use of growth charts for height and weight. Also, the Z-score can be calculated to represent the SD units away from the age-, sex-, and ethnic-specific median. For clinical care, the ISCD recommends the use of age- and sex-specific Z-scores, not the T-scores, when interpreting DXA results in children because it is inappropriate to compare the BMC and BMD of children with that of young adults (14). Currently, the ISCD recommends that the nomenclature of "low for chronological age" be used when the Z-score is below −2.0 (14), corresponding to the 2.3rd percentile for age.

In children, a low Z-score can be due to bone loss, poor accrual, small body size, or delayed maturation. Like a growth chart, these reference data are to be used as a screening tool to identify children with potential underlying problems in skeletal mineralization. It is important to consider the results of a DXA scan within the context of additional factors, such as fracture history, physical activity, medical history, medication use, nutritional status, maturation, and especially body size. This is particularly true for children with chronic diseases who often have delayed growth and maturation. Conversely, accelerated growth and maturation may result in an inflated BMC value for age that may convey false reassurance. Several approaches have been suggested to account for variation in skeletal size on DXA measures, such as calculation of bone mineral apparent density, BMC-for-height, and BMC-for-bone area (31–34). However, there are limited outcome data in children and no consensus as to the best approach (35, 36).

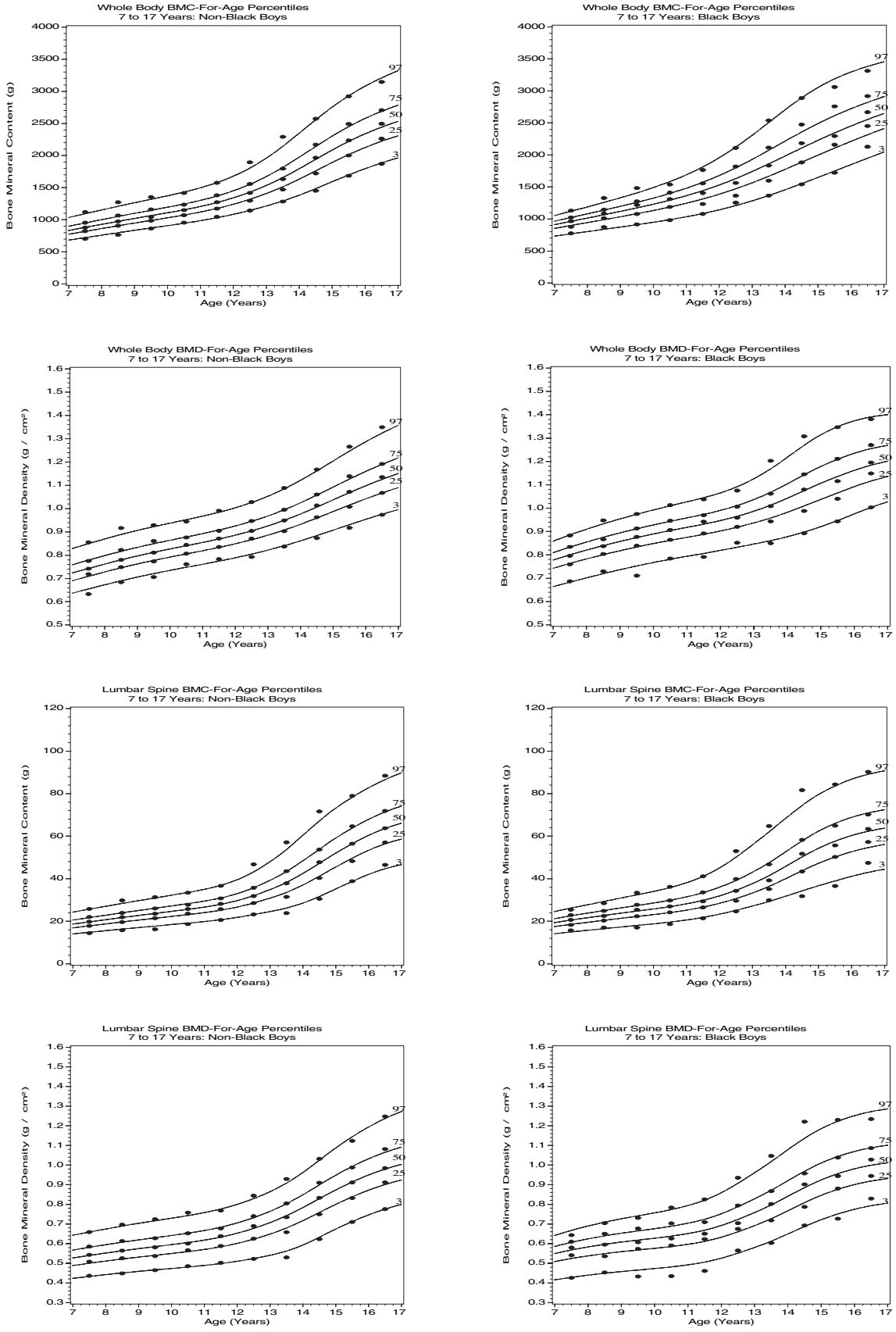

FIG. 1. Whole-body and lumbar spine BMC and BMD by age for non-Black (n = 580) and Black (n = 181) boys. Smoothed curves are given for the 3rd, 25th, 50th, 75th, and 97th percentiles. The plotted points represent the corresponding empirical percentile values for a given age group.

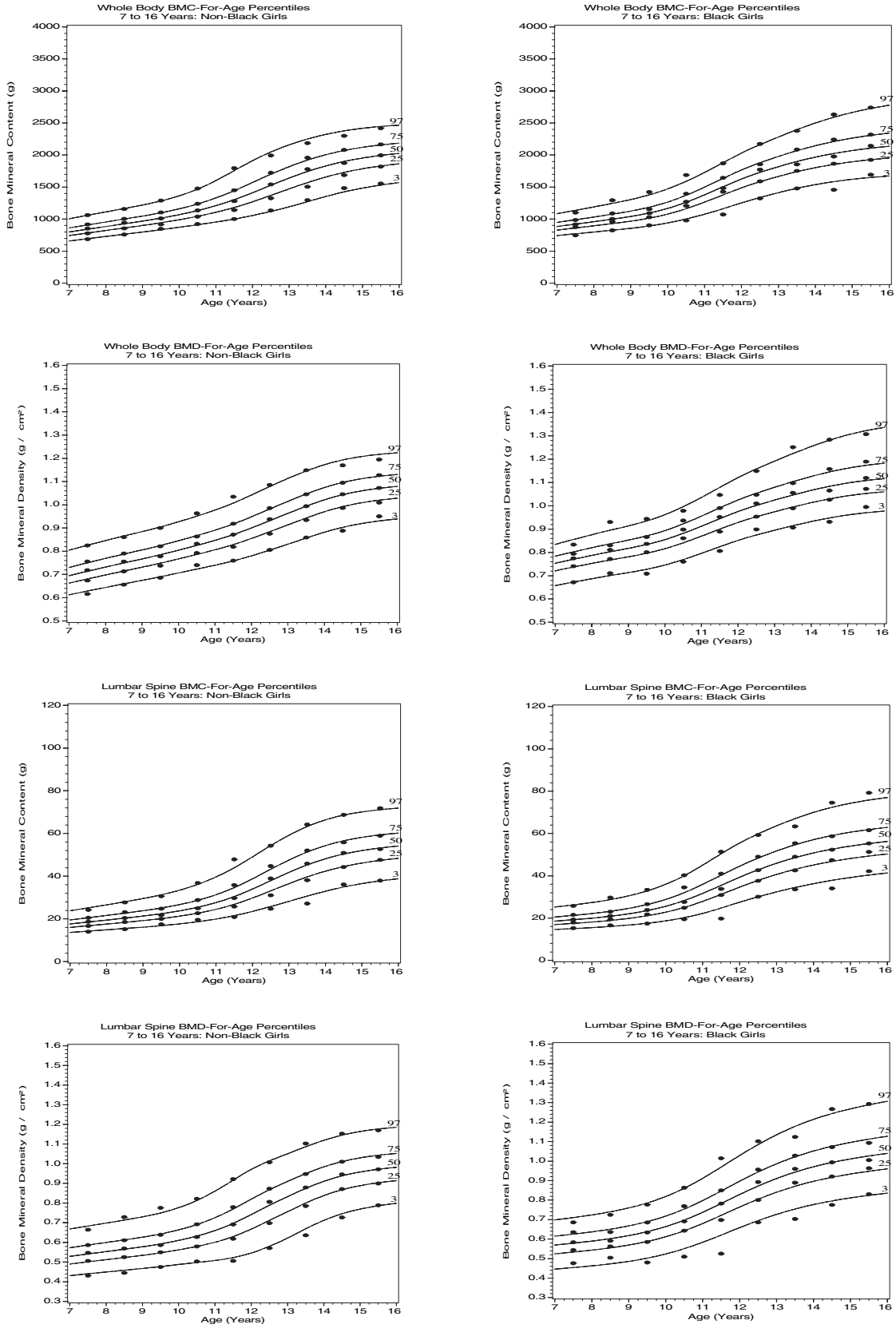

FIG. 2. Whole-body and lumbar spine BMC and BMD by age for non-Black (n = 603) and Black (n = 190) girls. Smoothed curves are given for the 3rd, 25th, 50th, 75th, and 97th percentiles. The plotted points represent the corresponding empirical percentile values for a given age group.

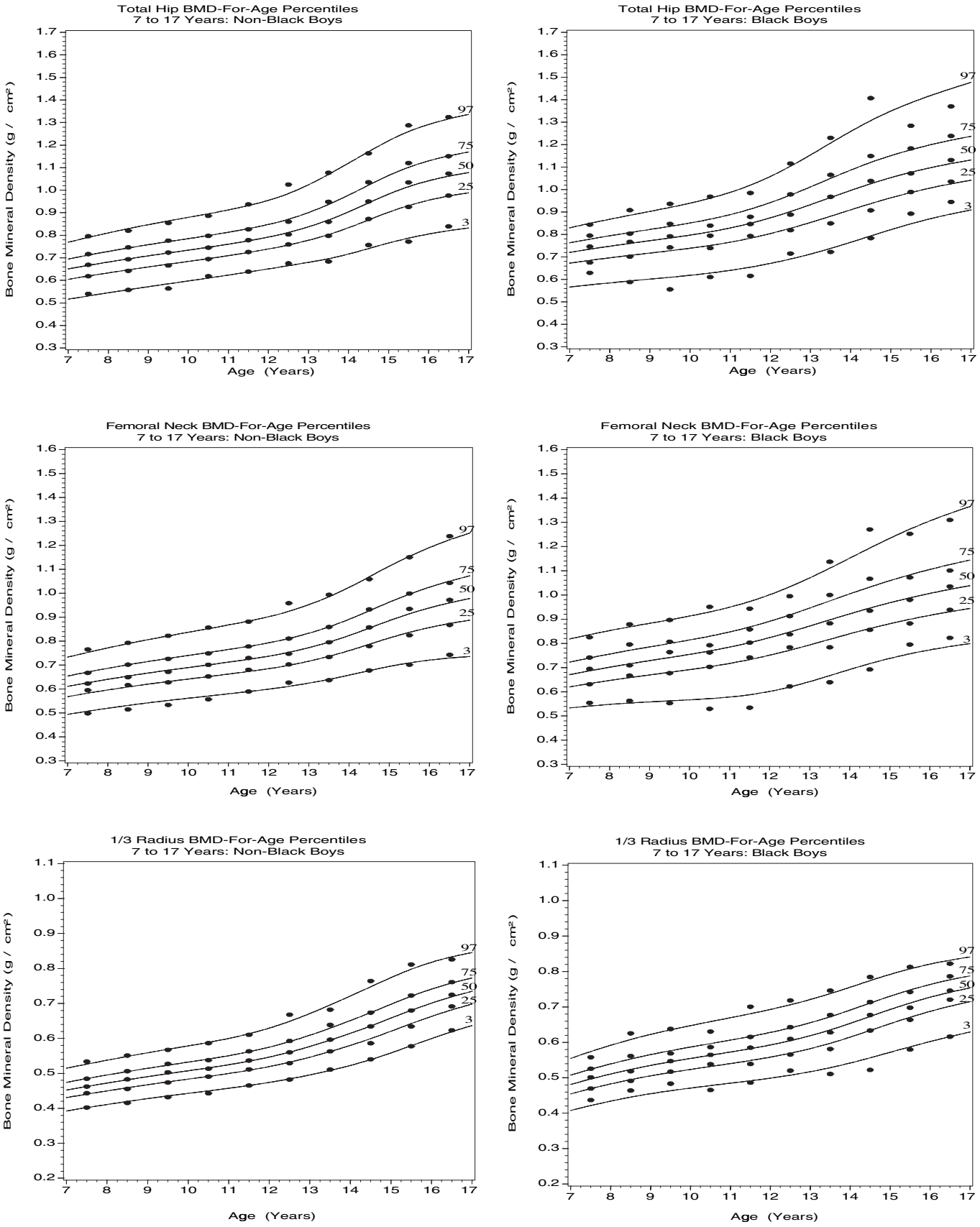

FIG. 3. Total hip, femoral neck, and one one third radius BMD by age for non-Black (n = 580) and Black (n = 181) boys. Smoothed curves are given for the 3rd, 25th, 50th, 75th, and 97th percentiles. The plotted points represent the corresponding empirical percentile values for a given age group.

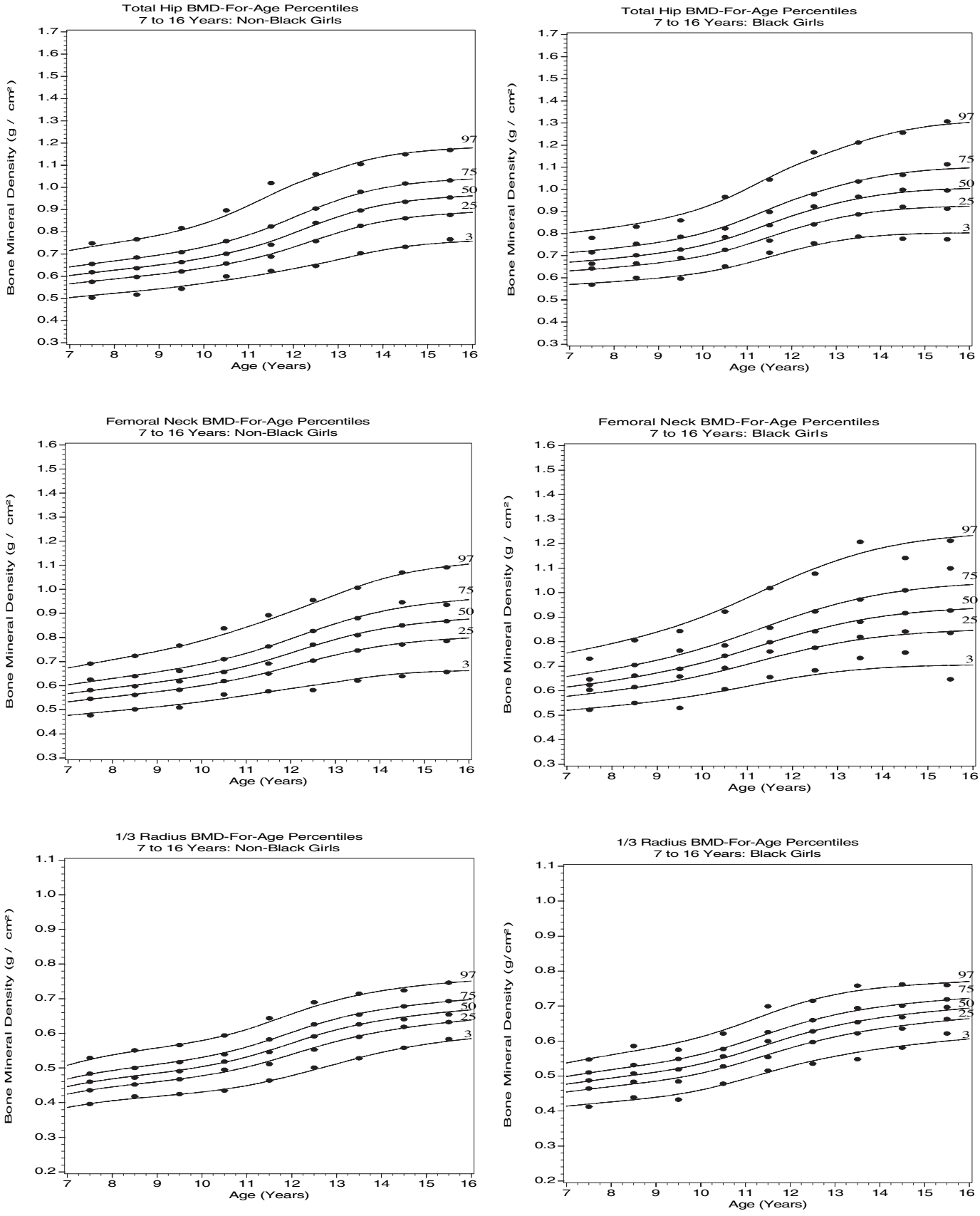

FIG. 4. Total hip, femoral neck, and one third radius BMD by age for non-Black (n = 603) and Black (n = 190) girls. Smoothed curves are given for the 3rd, 25th, 50th, 75th, and 97th percentiles. The plotted points represent the corresponding empirical percentile values for a given age group.

Finally, this study provides reference data for evaluation of bone mineral accrual at multiple skeletal sites. The optimal site for assessment of bone deficits will depend on the health condition being evaluated because medications and disease processes may differentially affect skeletal sites that are predominantly cortical *vs.* trabecular bone or weight-bearing *vs.* non-weight-bearing. Moreover, this is the first study to provide DXA-based reference data for the one third radius, a site that is primarily cortical bone, and often the only accessible part of the body for DXA imaging in patients with indwelling hardware and other physical limitations.

These reference data have some limitations. There were small numbers of Asians (n = 121) and Hispanics (n = 247), which limited our ability to identify ethnic-specific differences. The small number of Blacks may have affected the percentile estimation for the Black curves. This is evident when comparing the empirical percentiles to the estimated curves. Second, reference data are provided only for ages 7–16 yr for girls and 7–17 yr for boys. These limitations will be partly overcome when the study is completed and there are 6 yr of data. Also, the reference values provided herein are suitable for DXA scans acquired on the Hologic QDR 4500/Delphi/Discovery systems and are not appropriate for DXA scans acquired on other densitometers. Previous studies have reported that BMC and BMD values from older-model Lunar and Hologic densitometers differ by about 12% (37). Furthermore, BMD values reported from previous Hologic software versions may not be comparable owing to differences in automatic low-bone-density algorithms. Low-density software results in greater BMC and bone area and lower BMD for small, less dense bones (38). Cross-calibration studies are needed to develop conversion factors that are specific for machine and software type, body size, and skeletal site.

After adjustment of one site's calibration back to the factory setting, all study sites had excellent agreement in the BMC and BMD results for the spine, hip, and forearm scans of the traveling set of phantoms (differences $\leq$ 3%). However, there were larger differences (4 and 6%) in the phantom results for whole-body BMC and BMD between clinical sites. These calibration differences reflect a lower level of standardization of whole-body measurements by the manufacturer. The need for careful quality control and calibration of the whole-body scans on systems at clinical sites wanting to use these reference data cannot be overstated. Because of the greater variability in calibration of the whole-body scans, clinicians may want to rely more heavily upon regional scans in the assessment of bone health in children.

The percentiles reported here reflect those of a healthy population. Studies have shown BMD is related to fracture risk in healthy children (35, 39). Many researchers have speculated that optimal BMC and BMD in childhood and adolescence will reduce risk of osteoporotic fracture several decades later (1). These reference data provide the tool necessary for characterizing BMC and BMD status during growth and development so that future studies can investigate the lifelong consequences of bone mass accrual during childhood and adolescence.

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